Report of Investigations 2012-1

MIGRATED HYDROCARBONS IN EXPOSURE OF MAASTRICHTIAN NONMARINE STRATA NEAR SADDLE MOUNTAIN, LOWER COOK INLET, ALASKA

by
D.L. LePain, P.G. Lillis, K.P. Helmold, and R.G. Stanley

DGGS geologist David LePain investigates friable sandstone with migrated hydrocarbons near the base of the Saddle Mountain exposure. Magoon and others (1980) assigned the sandstone a Maastrichtian age on the basis of fossil pollen. Lillis (unpublished data) interpreted this oil as Tuxedni-sourced. Photograph taken by Rick Stanley.

Published by

STATE OF ALASKA
DEPARTMENT OF NATURAL RESOURCES

DIVISION OF GEOLOGICAL & GEOPHYSICAL SURVEYS

2012

Report of Investigations 2012-1

MIGRATED HYDROCARBONS IN EXPOSURE OF MAASTRICHTIAN NONMARINE STRATA NEAR SADDLE MOUNTAIN, LOWER COOK INLET, ALASKA

by
D.L. LePain, P.G. Lillis, K.P. Helmold, and R.G. Stanley

2012

This DGGS Report of Investigations is a final report of scientific research.
It has received technical review and may be cited as an agency publication.

STATE OF ALASKA
Sean Parnell, *Governor*

DEPARTMENT OF NATURAL RESOURCES
Daniel S. Sullivan *Commissioner*

DIVISION OF GEOLOGICAL & GEOPHYSICAL SURVEYS
Robert F. Swenson, *State Geologist and Director*

Publications produced by the Division of Geological & Geophysical Surveys (DGGS) are available for free download from the DGGS website (www.dggs.alaska.gov). Publications on hard-copy or digital media can be examined or purchased in the Fairbanks office:

Alaska Division of Geological & Geophysical Surveys
3354 College Rd., Fairbanks, Alaska 99709-3707
Phone: (907) 451-5020   Fax (907) 451-5050
dggspubs@alaska.gov
www.dggs.alaska.gov

Alaska State Library
State Office Building, 8th Floor
333 Willoughby Avenue
Juneau, Alaska 99811-0571

Alaska Resource Library & Information Services (ARLIS)
3150 C Street, Suite 100
Anchorage, Alaska 99503-3982

Elmer E. Rasmuson Library
University of Alaska Fairbanks
Fairbanks, Alaska 99775-1005

University of Alaska Anchorage Library
3211 Providence Drive
Anchorage, Alaska 99508-4614

This publication released by the Division of Geological & Geophysical Surveys was produced and printed in Fairbanks, Alaska, at a cost of $2.00 per copy. Publication is authorized by Alaska Statute 41, which charges the division “to determine the potential of Alaskan land for production of metals, minerals, fuels, and geothermal resources; the location and supplies of groundwater and construction materials; the potential geologic hazards to buildings, roads, bridges, and other installations and structures; and shall conduct such other surveys and investigations as will advance knowledge of the geology of Alaska.”

CONTENTS

FIGURES

MIGRATED HYDROCARBONS IN EXPOSURE OF MAASTRICHTIAN NONMARINE STRATA NEAR SADDLE MOUNTAIN, LOWER COOK INLET, ALASKA

by
D.L. LePain[1], P.G. Lillis[2], K.P. Helmold[3], and R.G. Stanley[4]

INTRODUCTION

Magoon and others (1980) described an 83-meter- (272-foot-) thick succession of Maastrichtian (Upper Cretaceous) conglomerate, sandstone, mudstone, and coal exposed on the south side of an unnamed drainage, approximately 3 kilometers (1.8 miles) east of Saddle Mountain in lower Cook Inlet (figs. 1 and 2). The initial significance of this exposure was that it was the first reported occurrence of nonmarine rocks of this age in outcrop in lower Cook Inlet, which helped constrain the Late Cretaceous paleogeography of the area and provided important information on the composition of latest Mesozoic sandstones in the basin. The Saddle Mountain section is thought to be an outcrop analog for Upper Cretaceous nonmarine strata penetrated in the OCS Y-0097 #1 (Raven) well, located approximately 40 kilometers (25 miles) to the south–southeast in Federal waters (fig. 1). Atlantic Richfield Company (ARCO) drilled the Raven well in 1980 and encountered oil-stained rocks and moveable liquid hydrocarbons between the depths of 1,760 and 3,700 feet. Completion reports on file with the Bureau of Ocean Energy Management (BOEM; formerly Bureau of Ocean Energy Management, Regulation and Enforcement, and prior to 2010, U.S. Minerals Management Service) either show flow rates of zero or do not mention flow rates. A fluid analysis report on file with BOEM suggests that a wireline tool sampled some oil beneath a 2,010-foot diesel cushion during the flow test of the 3,145–3,175 foot interval, but the recorded flow rate was still zero (Kirk Sherwood, written commun., January 9, 2012). Further delineation and evaluation of the apparent accumulation was never performed and the well was plugged and abandoned.

As part of a 5-year comprehensive evaluation of the geology and petroleum systems of the Cook Inlet forearc basin, the Alaska Division of Geological & Geophysical Surveys obtained a research permit from the National Park Service to access the relatively poorly understood ‘Saddle Mountain exposure’ that is located in the Lake Clark National Park and Preserve. This work was done in cooperation with the Alaska Division of Oil & Gas and U.S. Geological Survey (USGS) research geologists. This report expands on Magoon and others’ (1980) description of the exposure, presents new data on sandstone composition and reservoir quality, presents new geochemical data on petroleum extracted from the outcropping sandstone, and describes oil-bearing correlative strata penetrated by the Raven well. Although the exposure is more than a kilometer (0.6 mile) east of Saddle Mountain (fig. 2), in this report we variously refer to it as the Saddle Mountain succession, Saddle Mountain section, or the rocks at Saddle Mountain underlain by Upper Jurassic strata of the Naknek Formation.

GEOLOGIC SETTING

The Saddle Mountain exposure is situated along the west side of the Cook Inlet forearc basin, where Mesozoic and Cenozoic strata have been uplifted and deformed into a series of north–northeast-trending folds and east-dipping (basinward) hogbacks (figs. 1–3). The Saddle Mountain succession rests with angular discordance above the Pomeroy Arkose Member (Kimmeridgian–Late Jurassic) of the Naknek Formation and below the West Foreland Formation (Franklinian–early Eocene), both of which are exposed nearby (fig. 4; Magoon and others, 1980). The bounding unconformable contacts are unexposed at the Saddle Mountain location. Magoon and others (1980) mapped the Saddle Mountain section as laterally discontinuous, but showed a second exposure 8 kilometers (5 miles) to the southwest that included 15 meters (49 feet) of interbedded conglomerate and coal between the West Foreland and Naknek Formations. Magoon and others (1980) dated the Saddle Mountain succession as Maastrichtian on the basis of fossil pollen and correlated the succession to the lower of two coal-bearing nonmarine packages penetrated in the COST #1 well, located 50 kilometers (31 miles) to the south, in Federal waters (fig. 1). Both nonmarine packages in the COST #1 well include some of the same plant spores as found in the Saddle Mountain succession. Correlation with the lower nonmarine package in that well is based on similarities in the modal composition of sandstone. These authors noted the younger coal-bearing succession in the COST #1 well has

[1]Alaska Division of Geological & Geophysical Surveys, 3354 College Rd., Fairbanks, Alaska 99709-3707
[2]U.S. Geological Survey, P.O. Box 25046, Mail Stop 977, Denver, Colorado 80225
[3]Alaska Division of Oil & Gas, 550 W. 7th Ave., Anchorage, Alaska 99501
[4]U.S. Geological Survey, 345 Middlefield Road, MS 969, Menlo Park, California 94025

modal compositions similar to sand in nearby exposures of the West Foreland Formation. Middle Jurassic mudstone of the Red Glacier Formation of the Tuxedni Group is present in outcrop at Red Glacier, approximately 13 kilometers (8 miles) west of the Saddle Mountain exposure. Based on reported minimum thicknesses for stratigraphic units mapped in the area by Detterman and Hartsock (1966), and taking the mid-range thickness for units reported to vary in thickness from zero to some maximum value, at least 2,100 meters (6,890 feet) of Mesozoic strata lie between the Saddle Mountain section and the top of the Middle Jurassic Red Glacier Formation. The Tuxedni Group, including the Red Glacier Formation, is thought to include the main oil-prone source rocks responsible for generating oil in Cook Inlet basin (Magoon and Anders, 1992). These rocks and their subsurface equivalents in the forearc basin are thought to have sourced the oil in upper Cook Inlet fields, residual hydrocarbons at Saddle Mountain, seeps in Middle Jurassic rocks on the Iniskin Peninsula, and the oil accumulation in the Raven #1 well (Lillis, unpublished data, 2010; see below).

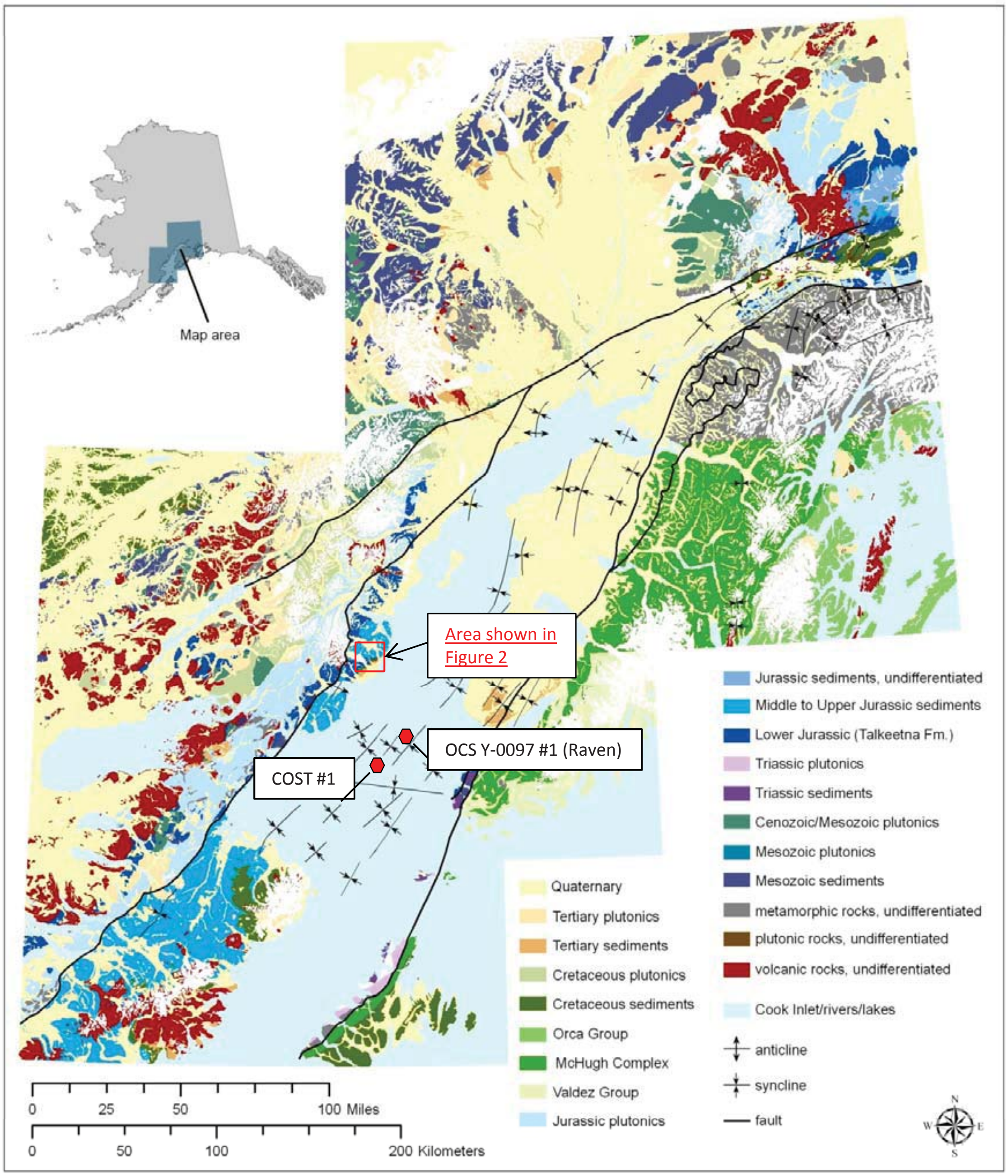

Figure 1. Generalized geologic map of the Cook Inlet region (modified from Wilson and others, 2009).

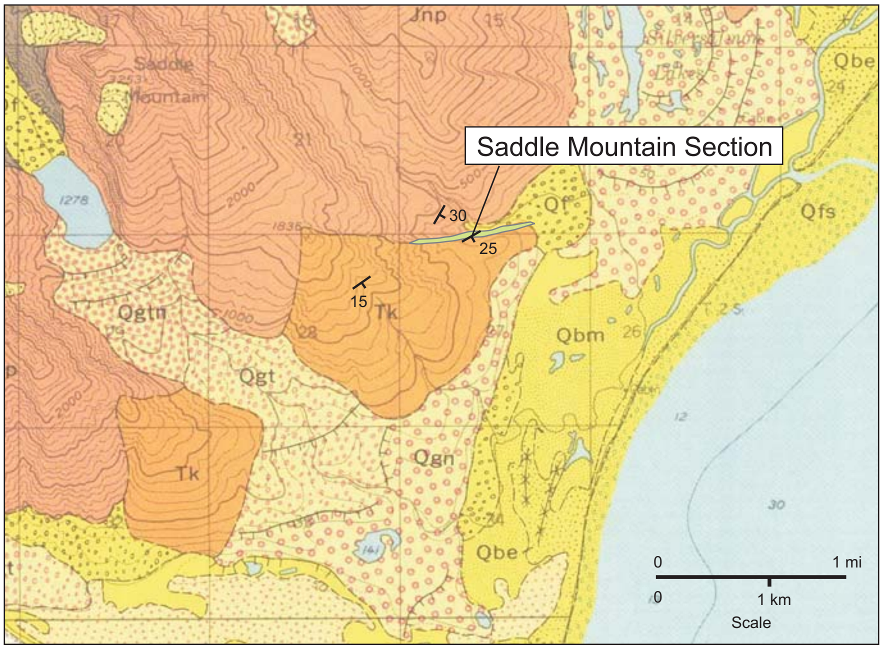

Figure 2. Detailed geologic map of the Saddle Mountain area showing the location of the Saddle Mountain exposure and section (green polygon) relative to Saddle Mountain (modified from Detterman and Hartsock, 1966).

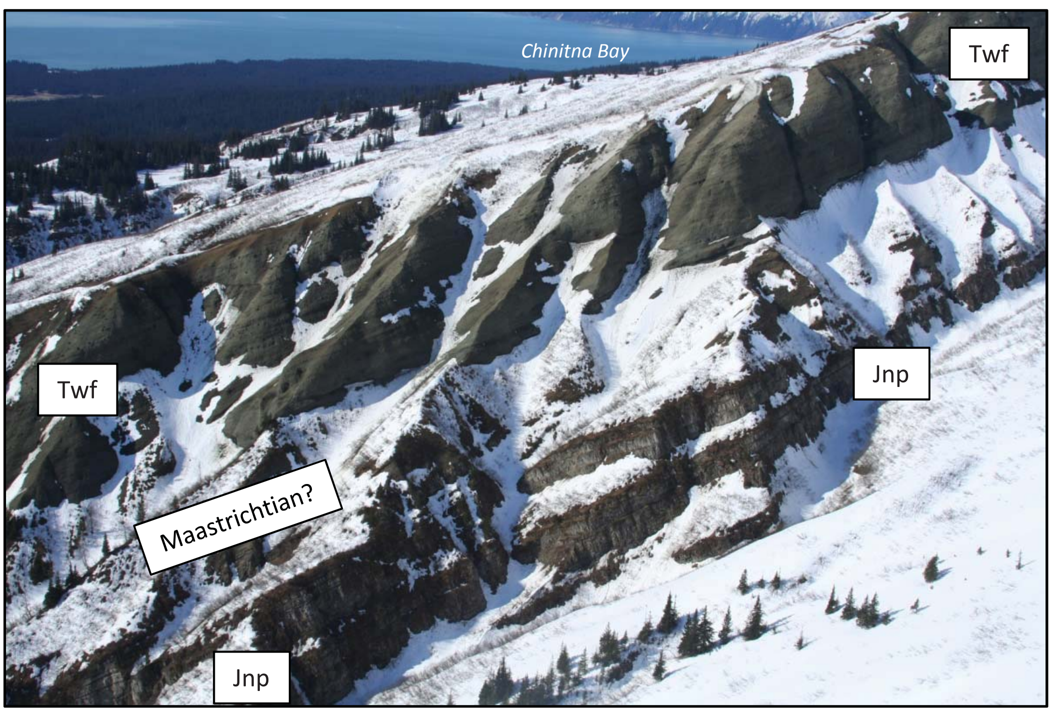

Figure 3. Photograph showing east-dipping beds of the West Foreland Formation (Twf; Eocene) overlying east-dipping beds of the Pomeroy Arkose Member of the Naknek Formation (Jnp; Kimmeridgian). Location is approximately 10 kilometers (6 miles) south–southeast of the Saddle Mountain section, southwest of the area shown in figure 2. View is toward the south with Chinitna Bay visible in the distance. Photograph was taken the first week in May, 2010.

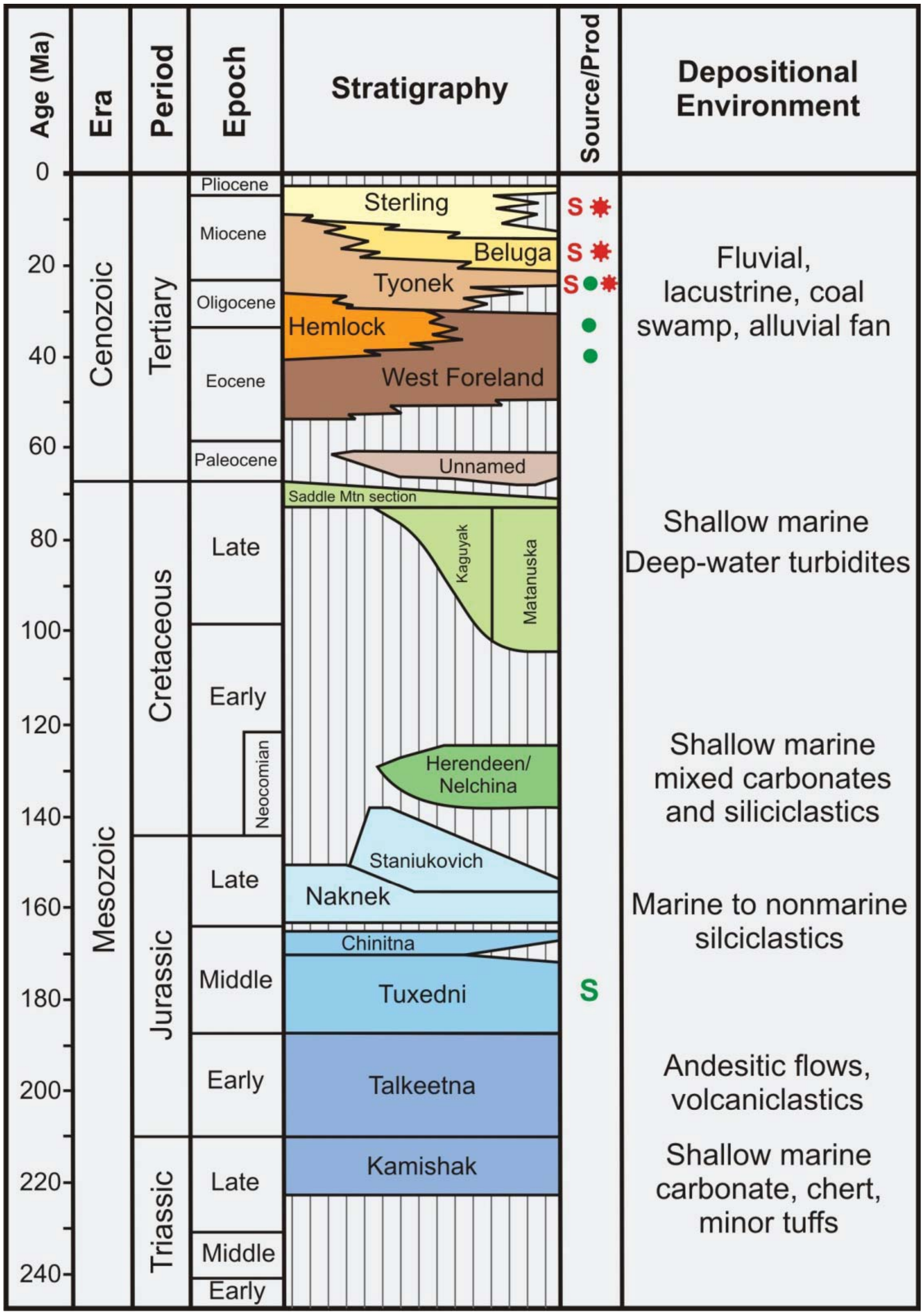

Figure 4. Generalized stratigraphic column for Cook Inlet basin. The vertical line separating the Kaguyak and Matanuska Formations represents the arbitrary dividing line at the latitude of Kalgin Island: Upper Cretaceous strata south of Kalgin Island are assigned to the Kaguyak Formation and Upper Cretaceous strata north of the island are assigned to the Matanuska Formation (Magoon and Egbert, 1986). Red **S** *is gas source rock; green* **S** *is oil source rock; filled red star* * *is gas production; filled green circle* ● *is oil production. Figure redrawn from Swenson (2003).*

A brief note regarding formation nomenclature is appropriate before continuing. As noted in the preceding paragraph, available age control suggests the Saddle Mountain section is Maastrichtian (Magoon and others, 1980). On this basis the Saddle Mountain section is thought to be correlative with the Kaguyak Formation, which is exposed along the west coast of Shelikof Strait, south of Cape Douglas. Hastings and others (1983), on the basis of drilling results and high quality seismic data obtained in the early 1980s, proposed to extend the Kaguyak to include Albian through Maastrichtian strata. They proposed three members including, in ascending order: (1) Unnamed Albian to Cenomanian strata, (2) Middle Member, and (3) Saddle Mountain Member. The latter member corresponds to the Saddle Mountain section described by Magoon and others (1980) and is the subject of this report. Hastings and others' (1983) work is significant as it provides paleogeographic context for the Saddle Mountain section. Their work suggests that the Saddle Mountain section grades to marine shelf deposits toward the forearc basin axis (eastward and southeastward in present-day coordinates), and that marine shelf deposits grade further basinward to slope and deeper water deposits inferred to include deepwater facies similar to parts of the type Kaguyak Formation. These authors did not provide data to support their conclusions and they did not identify and document type sections for each of their proposed members and publish this documentation in a peer-reviewed, publically available report, as required by the North American Stratigraphic Code (1983). Consequently, their proposed members cannot be viewed as formally defined stratigraphic units. The Kaguyak Formation was defined by Keller and Reiser (1959), who designated a type section that includes 1,390 meters (4,560 feet) of interbedded shale, siltstone, and sandstone exposed along the sea cliffs from Big River to Swikshak River. Detterman and Miller (1985) reexamined the type section and interpreted the succession as a prograding submarine fan complex. The Saddle Mountain section includes a dramatically different suite of facies as described by Magoon and others (1980) and in this report. Therefore, it is inappropriate to include the succession as part of the Kaguyak Formation and it should not be referred to as the Saddle Mountain Member in the peer-reviewed geologic literature.

OUTCROP DESCRIPTION

The description presented here expands on Magoon and others' (1980) description and is keyed to their measured stratigraphic section, which has been redrafted and shown here as figure 5. Approximately 83 meters (~280 feet) of brown-weathering sandstone, brown- and gray-weathering mudstone, dark-gray-weathering carbonaceous mudstone with coaly streaks, and pebble–cobble conglomerate are discontinuously exposed along the south valley wall of an unnamed creek (figs. 2 and 6a). The base of the exposure is approximately 6 meters (20 feet) above creek level. The lower 30 meters (98 feet; lower sandstone package) consists of highly weathered, brown- and green-weathering, medium-bedded, fine- to coarse-grained sandstone (figs. 5, 6a, and 6b). From the air, bedding appears laterally continuous over the extent of the exposure, but upon closer inspection beds cannot be traced laterally more than 5–10 meters (16–33 feet; fig. 6b). Weathering character suggests beds range from 10 centimeters (4 inches) to more than a meter (3.3 feet) thick (fig. 6b); trough cross-bedding in sets approximately 20 centimeters (8 inches) thick are visible locally. Sandstones are devoid of macroinvertebrate and trace fossils. At least two fining-upward packages are present in the basal 30 meters (98 feet; fig. 5). Calcite-cemented sandstone is common in this part of the Saddle Mountain section (fig. 5). The basal 3.5 to 4 meters (11.5 to 13 feet) of the lower sandstone package is cemented and includes concretions. A prominent 2- to 2.5-meter- (6.5- to 8.2-foot-) thick bed of light brown friable sandstone overlies the concretionary bed. When undisturbed, the friable sandstone bed emits a very faint and fleeting hydrocarbon odor (fig. 6c). Freshly excavated surfaces emit a strong to very strong, but still fleeting, hydrocarbon odor. Other than appearing friable, this bed lacks visible hydrocarbon stain (fig. 6d). Rock samples for geochemical and petrographic analysis were collected from freshly excavated cuts in this bed.

The upper 5 to 10 meters (16 to 33 feet) of the lower part of the exposure (20 to 30 meter [66 to 98 foot] interval on fig. 5) extends downstream several tens of meters, where the exposure then continues discontinuously up a steep slope for another 50 plus meters (164 plus feet; fig. 6a). The next 20 meters (66 feet) consists of interbedded brown-weathering siltstone with thin coaly streaks, dark brown siltstone with thin, discontinuous carbonaceous drapes, and medium- to coarse-grained sandstone and pebble–cobble conglomerate. Magoon and others (1980) show the latter two lithologies arranged in a single fining-upward succession between 40 and 48 meters in their measured section (fig. 5). They also show several thin coal seams that are more accurately carbonaceous mudstone or siltstone with thin coaly streaks (see beds at 30 meters, 37.5 meters, and 48 meters; fig. 7a). Sandstone and siltstone are locally rooted and include coalified woody material (figs. 6b and 7c).

The upper 30 plus meters (98 plus feet) of the exposure consists of interbedded conglomerate, sandstone, and coal (figs. 6a and 7d). Conglomerates are clast-supported, include tightly packed, poorly sorted matrix of fine- to very-coarse-grained sandstone, and appear disorganized (no visible internal bedding or clast fabric). Magoon and others (1980) show large-scale cross-stratification between 50 and 67 meters (164 and 220 feet; fig. 5), but this was not noted during our examination of the exposure. In our experience with conglomerates, large-scale cross-stratification is commonly best viewed from a distance (20–30 meters; 60–100 feet); given the valley topography and vegetation, we were unable to see it from a

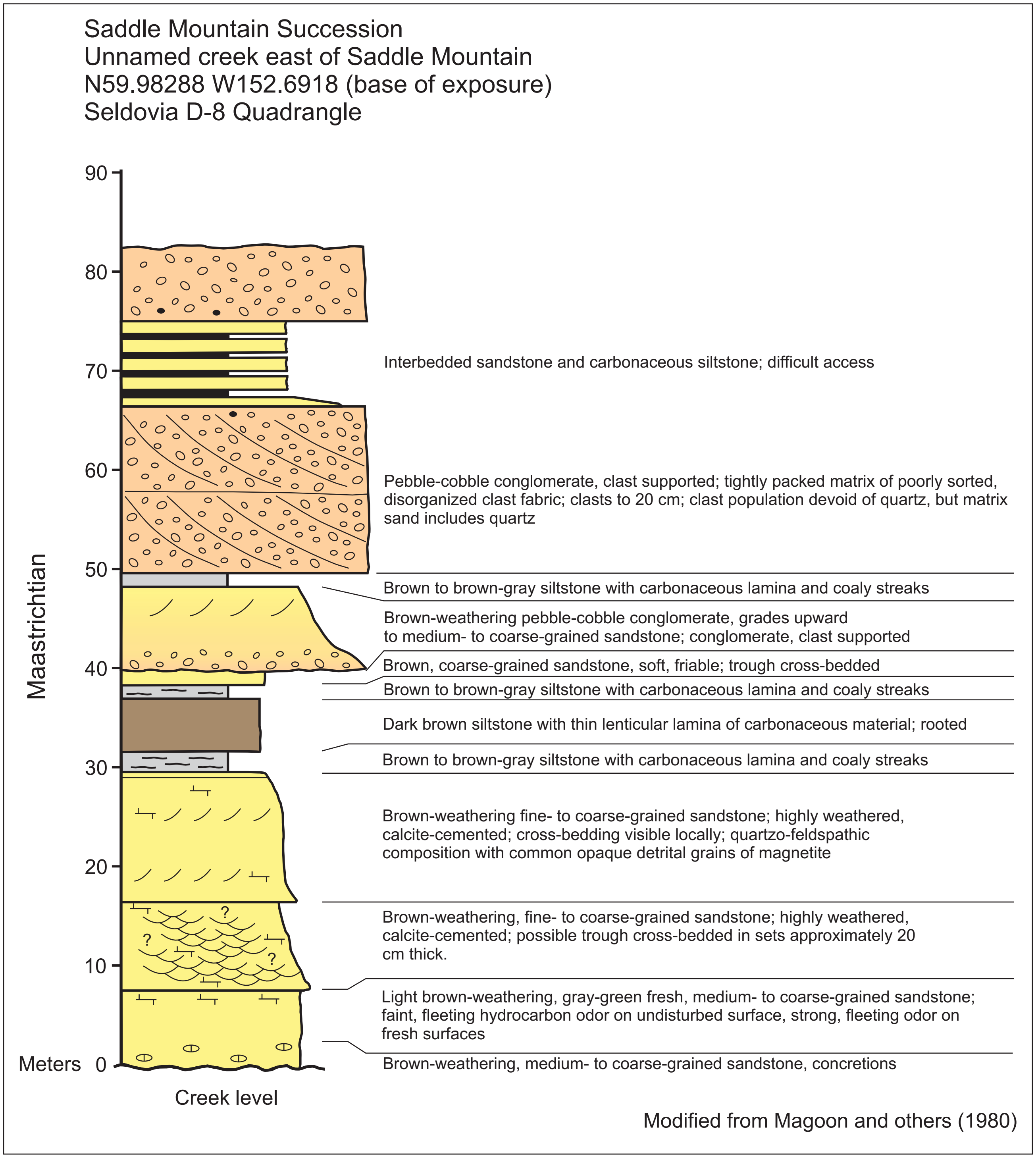

Figure 5. Measured stratigraphic section showing the Saddle Mountain succession. Modified from Magoon and others (1980).

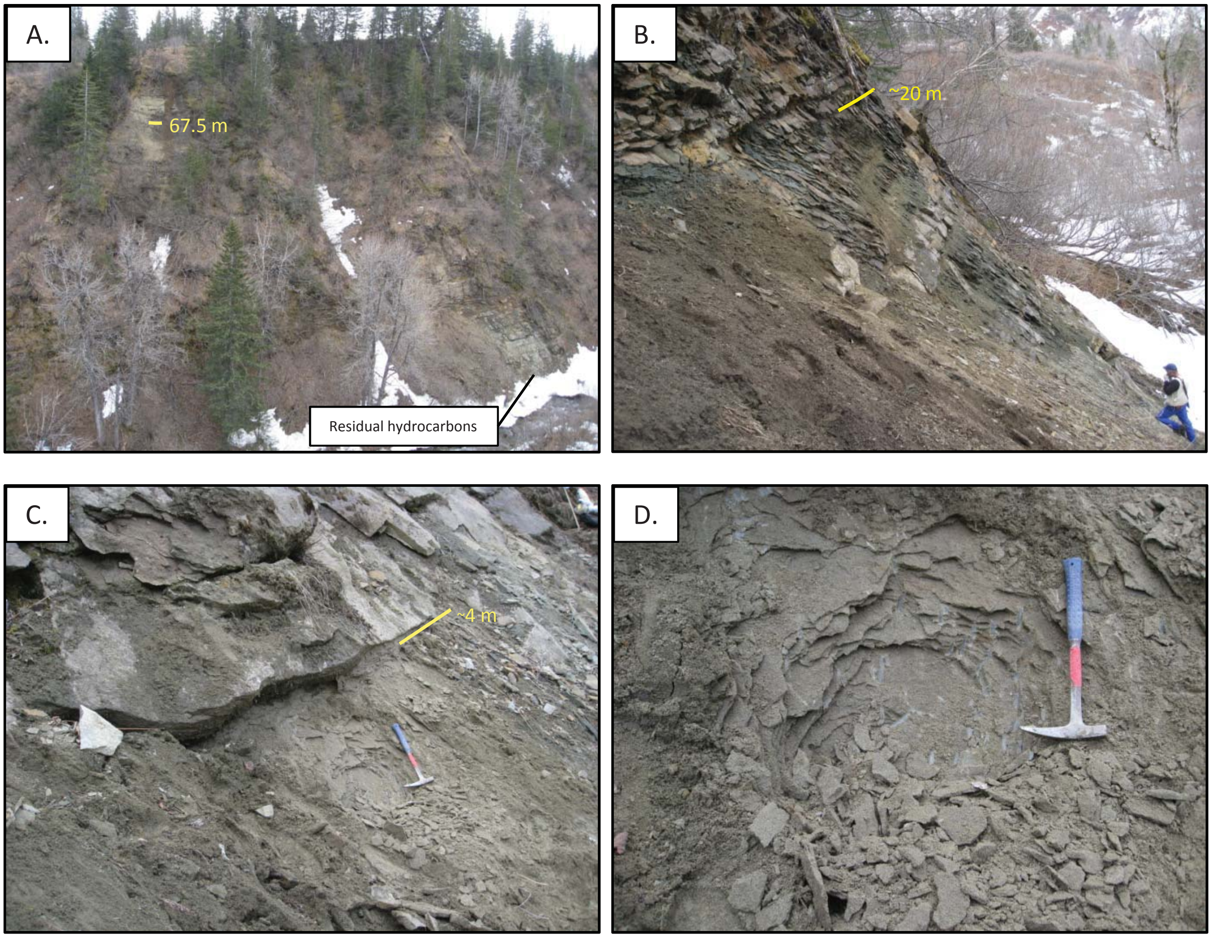

Figure 6. Photographs showing selected features in the lower 22 meters (72 feet) of the Saddle Mountain section. A. Exposure viewed from the air at low elevation showing up to 70 meters (230 feet). View toward the southeast. B. Lower 22 meters (72 feet) of the Saddle Mountain section showing bedding style in fine- to coarse-grained sandstone. Geologist for scale. C. and D. Friable sandstone with residual hydrocarbons below 4 meter (13 foot) level. Hammer is 40 centimeters (15.7 inches) long and leaning against the friable sandstone. The undisturbed bed emitted a faint and fleeting hydrocarbon odor, whereas freshly excavated sand emitted a moderate to strong hydrocarbon odor. Many sandstone beds in the lower 20 meters (65 feet) of the section weather a medium to dark green.

distance. Coals that are shown interbedded with sandstone from 67 to 74 meters (220 to 243 feet) in figure 5 may, in fact, be carbonaceous mudstones with coaly streaks similar to those encountered lower in the section, but this was not verified due to their inaccessibility (fig. 7d). The conglomerate bed capping the section was not examined for the same reason. This bed could be basal West Foreland Formation or Quaternary gravel. The degree of lithification/compaction, at least from a distance, appears similar to conglomerates lower in the section and to nearby exposures of the West Foreland, which leads us to discount the possibility that the bed is Quaternary gravel.

The absence of marine macrofossils combined with the presence of carbonaceous mudstones with coaly laminae, overall bedding style in sandstones (laterally discontinuous), and the disorganized appearance of conglomerates suggests the Saddle Mountain section was deposited in a nonmarine setting. Proximity to the shoreline is unknown. If correlations with the COST #1 and Raven #1 well are correct, the coeval shoreline could have been tens of kilometers away from the Saddle Mountain location.

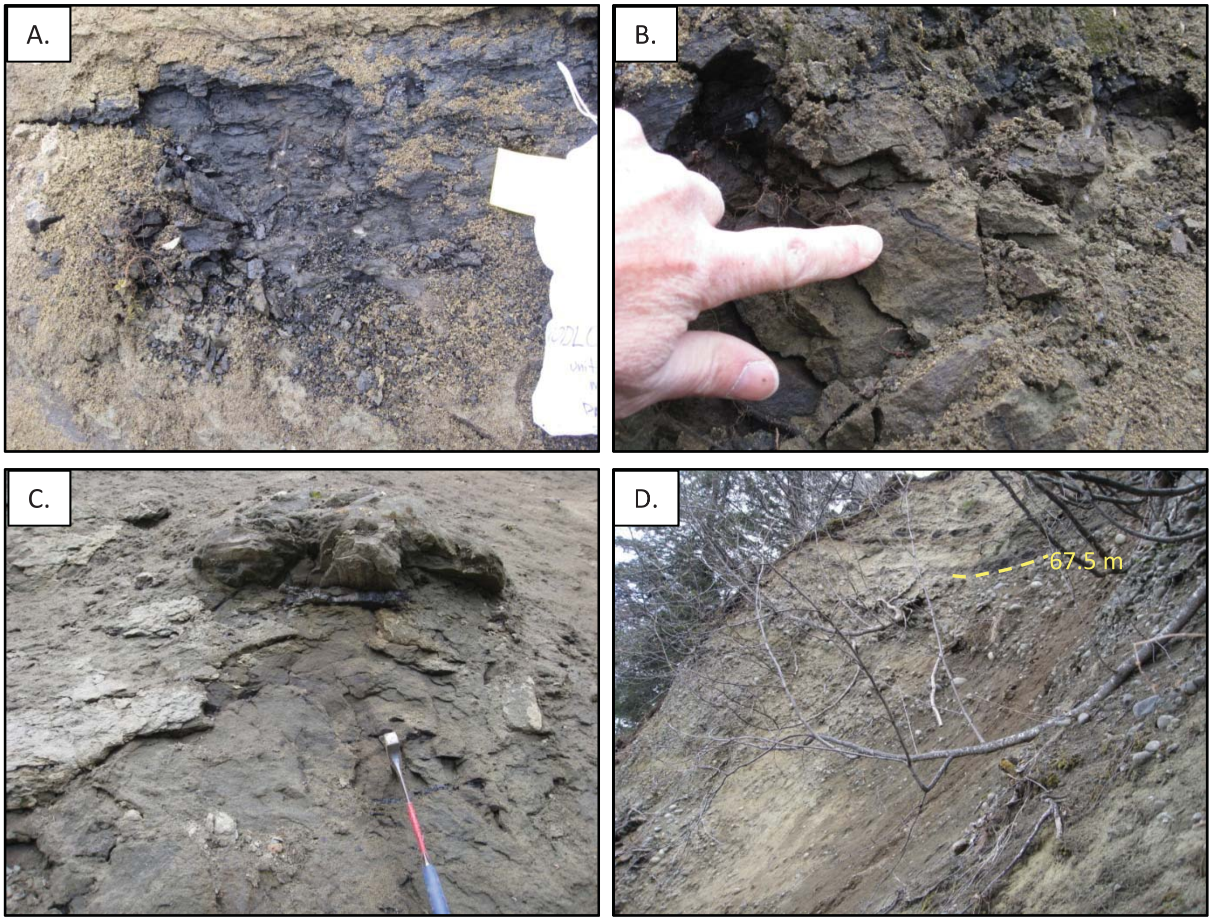

Figure 7. Photographs showing selected features in the upper 50 meters (164 feet) of the Saddle Mountain section. A. Carbonaceous mudstone. Sample bag is 25 centimeters (9.8 inches) long. B. Rhizolith at approximately 36 meters (118 feet) in the measured section. C. Highly weathered sandstone at approximately 46 meters (151 feet) in the measured section. Note coalified wood fragments oriented sub-parallel to bedding, below head of hammer and below overhanging rock. D. Interbedded pebble–cobble conglomerate, sandstone, and coal in upper 20 meters (65 feet) of the Saddle Mountain section.

SANDSTONE AND CONGLOMERATE COMPOSITIONS AND RESERVOIR QUALITY

Sandstone in the Saddle Mountain section is quartzo-feldspathic, and includes distinctive granitic rock fragments (fig. 8a), a distinctive green-colored mica, and a locally abundant opaque mineral (magnetite?; fig. 8a). Most beds are deeply weathered, but well indurated. Calcite is locally common and, at least in some beds, has replaced detrital grains (probably feldspar; fig. 8b). Most pores are completely, or nearly completely, filled with diagenetic clay (fig. 8a). Clay composition is unknown, but is probably chlorite or mixed-layer chlorite/smectite. Porosity and permeability in the indurated sandstone are both low—8.3 percent and 0.043 millidarcy (Klinkenberg; air permeability is 0.066 millidarcy). The friable sandstone with residual hydrocarbon has a similar framework composition, but includes much less calcite and significantly less pore-filling clay (as cement and detrital feldspar replacement; figs. 8c and 8d). Porosity and permeability in the friable sandstone with residual hydrocarbon is 18.9 percent and 8.5 (Klinkenberg; air permeability is 10.7), respectively. The mean modal composition reported by Magoon and others (1980) is $Q_{32}F_{40}L_{28}$, which differs somewhat from our modal mean (from only two sandstone samples) of $Q_{26}F_{20}L_{54}$. Lithic grains include, in order of decreasing abundance, plutonic rock fragments (mostly granitic), volcanic rock fragments (felsic and mafic varieties), chert, and minor metamorphic rock fragments (schist).

The conglomerate is devoid of quartz clasts and the population is dominated by dioritic and granitic intrusives and mafic and felsic volcanics. Many of the plutonic rocks appear foliated, indicating derivation from a source terrain with metaplutonic rocks. An abbreviated clast count (50 counts) from the base of the conglomerate at 50 meters (164 feet; fig. 5)

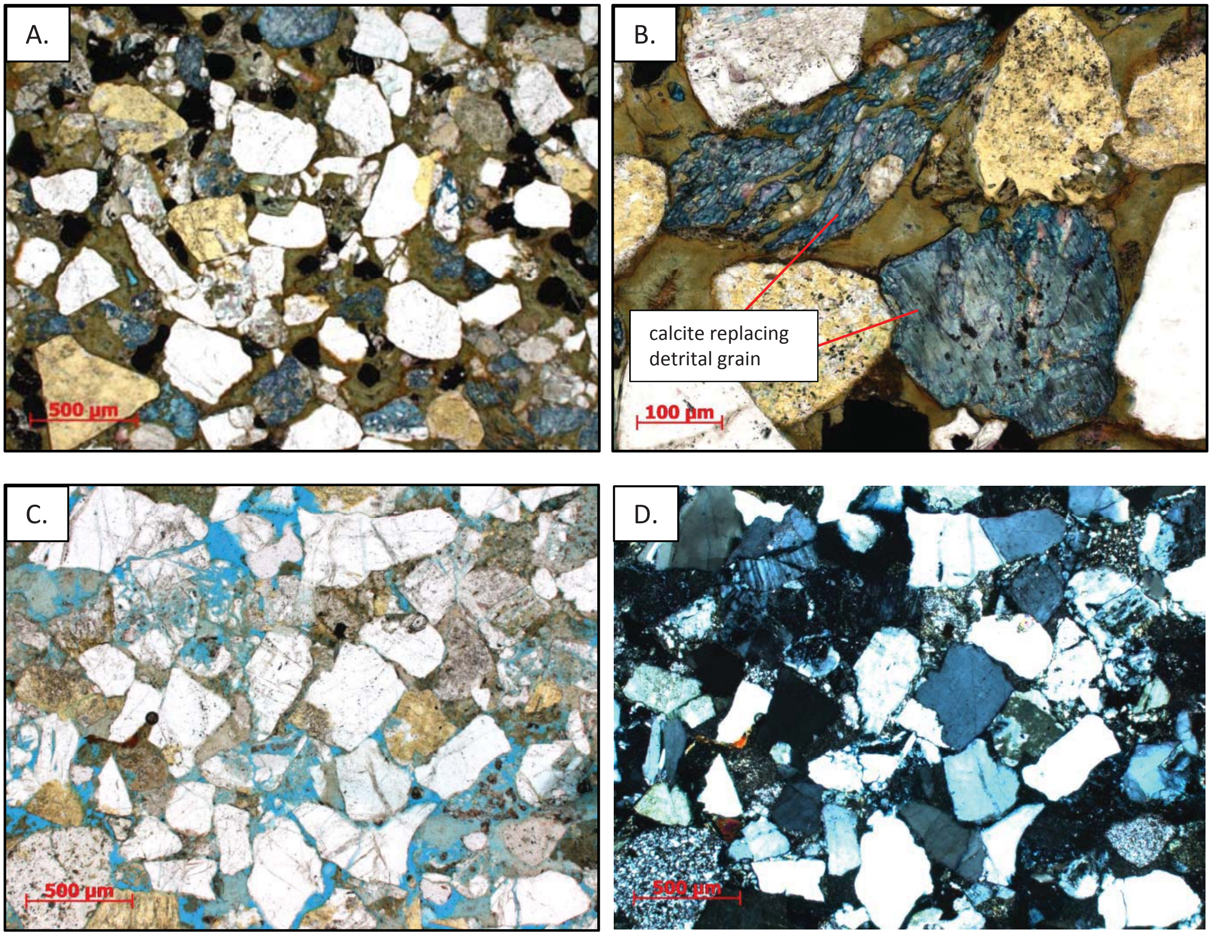

Figure 8. Photomicrographs of sandstone in the lower 10 meters (33 feet) of the Saddle Mountain section. A. Sandstone composed largely of quartz, potassium feldspar, and granitic rock fragments, and pore-filling clay minerals. Clay is most likely chlorite or mixed-layer chlorite/smectite. Opaque grains are most likely magnetite. Plane light. B. Calcite replacing detrital grains, possibly feldspar. Clay is chlorite or chlorite/smectite. C. Friable sandstone with residual hydrocarbons. Sand consists of quartz, potassium and plagioclase feldspar, and lithic grains. Lithic grains include plutonic rock fragments (granitic), volcanic rock fragments (felsic and mafic), chert, and minor metamorphic rock fragments (schist). Note porosity shown in blue. Compare with A. Note also the lack of pore-filling clay. Plane light. D. As in C., but with cross-polarized light.

includes 64 percent mafic volcanic rocks, 16 percent non-foliated intrusive rocks, 14 percent foliated intrusive rocks, and 6 percent felsic volcanic rocks. Of the mafic volcanic rocks, slightly more than 88 percent of the clasts were field classified as greenstone and the remaining as basalt or andesite. The clast compositions closely resemble compositions in the West Foreland Formation to the north, near Capps Glacier (Tyonek Quadrangle), as determined through numerous clast counts (LePain, unpublished field notes; Helmold, unpublished field notes; Finzel, 2010).

GEOCHEMISTRY

A sandstone sample collected from the Saddle Mountain section and containing residual hydrocarbons was analyzed by the U.S. Geological Survey Energy Resources geochemistry laboratory in Denver, Colorado (figs. 5, 6c, and 6d). Residual hydrocarbons were extracted from the sample by soaking the sand in chloroform, filtering the extract, and removing the excess solvent by rotoevaporation. The extract was analyzed by gas chromatography using an HP6890 gas chromatograph with a flame ionization detector (GC-FID) and by gas chromatography–mass spectrometry (GC-MS) using an Agilent MSD in full scan mode. The GC-FID results show that the oil has experienced mild biodegradation as evidenced by the absence of normal alkanes, and the presence of acyclic isoprenoids (including pristane and phytane) and an unresolved complex mixture (UCM) or "hump" shaped baseline. A mass chromatogram (m/z 191) was constructed from the full scan run (fig. 9). Biomarker parameters selected for correlation include pristane/phytane (from the GC-FID), C_{23} tricyclic terpane/C_{24} tetracyclic terpane, C_{27} 18α–trisnorhopane/C_{27} 17α–trisnorhopane (Ts/Tm), 17α–diahopane/C_{30} 17α–hopane, C_{29} 17α–norhopane/C_{30} 17α–hopane and C_{31} 22R homohopane/C_{30} 17α–hopane. Results are shown on figure 9. All of the parameters are within the range of composition of Tuxedni-sourced oil (Lillis, unpublished data, 2010), except for the diahopane/hopane ratio (0.26) which is slightly higher. Nevertheless, the oil stain is interpreted to be Tuxedni-sourced oil.

The oil from the drill stem test (DST) of the Cretaceous sandstone in the OCS Y-0097 #1 (Raven) well was characterized by Magoon and Anders (1992) as a mixed Middle Jurassic Tuxedni–Upper Triassic sourced oil. Lillis (unpublished data, 2010) interpreted a recent analysis of this oil as Tuxedni-sourced oil.

DISCUSSION

The Saddle Mountain exposure provides important information on the Late Cretaceous paleogeography and the distribution of oil-prone source rock in lower Cook Inlet. As pointed out by Magoon and others (1980) the exposure demonstrated the presence of Upper Cretaceous nonmarine rocks in lower Cook Inlet. They interpreted the plant spore assemblage as Maastrichtian (latest Cretaceous) and lithofacies as recording nonmarine deposition close to the coeval shoreline. The presence of nonmarine facies combined with the laterally discontinuous outcrop pattern (fig. 2; Magoon and others, 1980, their fig. 2) suggest deposition of the Saddle Mountain section in a broad paleovalley incised into the underlying Naknek Formation. As noted earlier, the Saddle Mountain section was correlated to coal-bearing strata capping a regressive succession in the COST #1 well (Magoon and others, 1980, their fig. 5).

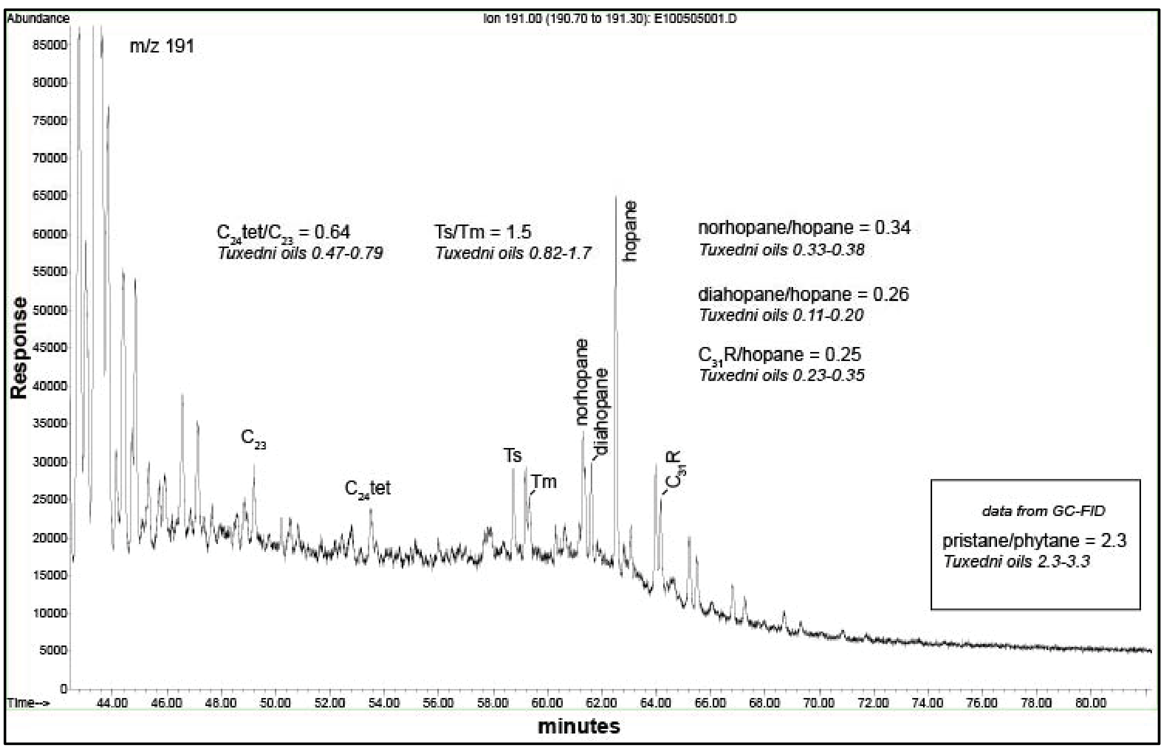

Figure 9. Mass chromatogram (m/z 191) constructed from a GC-MS full-scan run of extracted oil stain in a friable sandstone near the base of the Saddle Mountain section. Biomarker peaks identified are: C_{23} tricyclic terpane (C_{23}), C_{24} tetracyclic terpane (C_{24}tet), C_{27} 18α–trisnorhopane (Ts), C_{27} 17α–trisnorhopane (Tm), C_{29} 17α–norhopane, 17α–diahopane, C_{30} 17α–hopane, and C_{31} 22R homohopane. Also shown are biomarker parameters of the extract that are within the range of composition of Tuxedni-sourced oil produced in Cook Inlet.

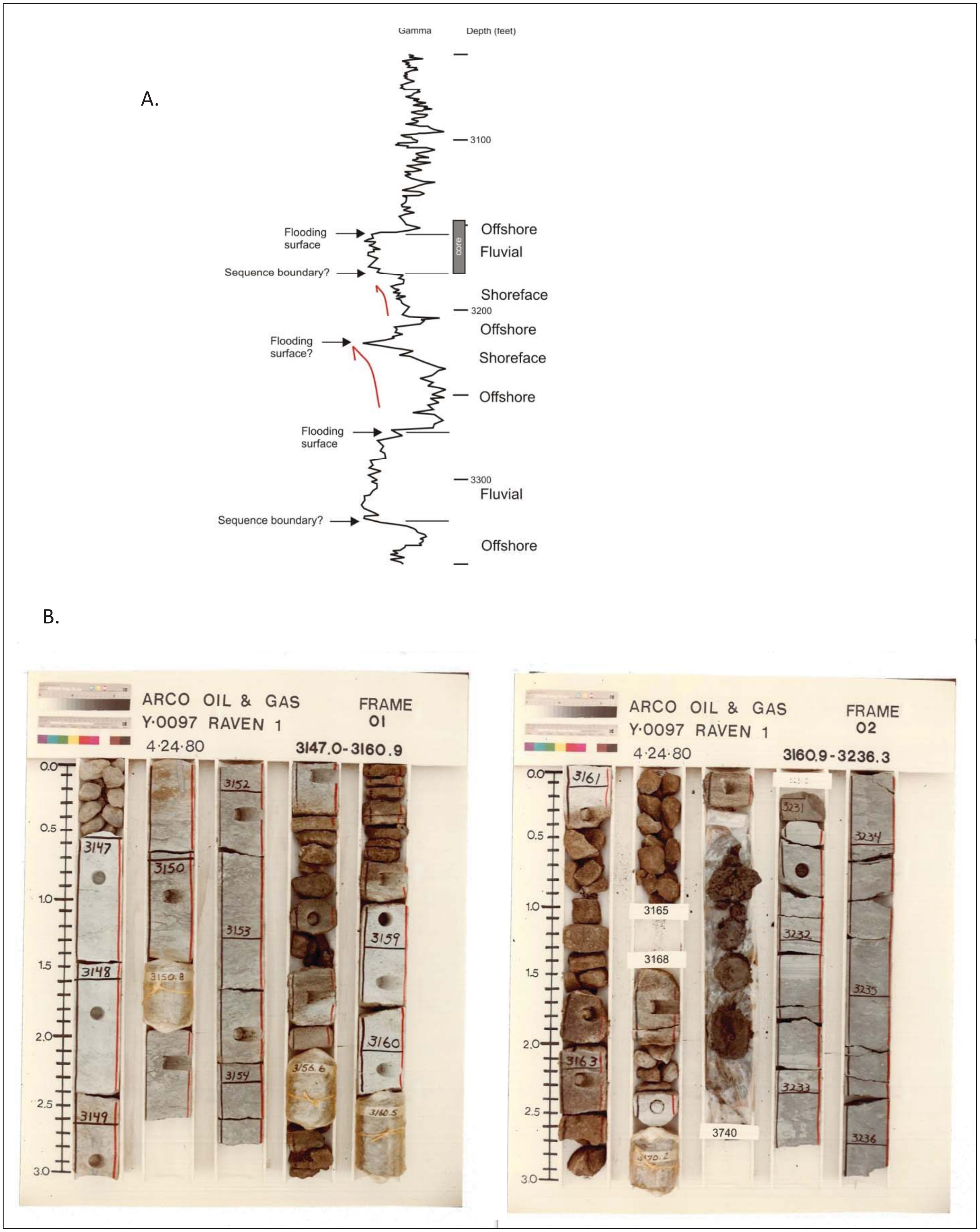

Figure 10. Gamma log and core photos from the OCS Y-0097 #1 (Raven) well. A. Gamma log for the interval 3,050–3,350 feet depth showing interpreted depositional environments. B. Core photographs showing heavily oil-stained Maastrichtian sandstones between 3,146 and 3,236 feet. The Saddle Mountain section is an outcrop analog for this interval in the Raven well. Gamma-ray log and core photos obtained from the U.S. Bureau of Ocean Energy Management (formerly known as the U.S. Minerals Management Service)

Wireline log motifs and core photos suggest a similar suite of facies in the Raven #1 well between the depths of 3,050 and 3,350 feet, with the notable difference being the presence of marine facies and numerous oil shows and liquid hydrocarbon in the well (figs. 10a and 10b; wireline logs, ARCO core descriptions, and ARCO core photos for OCS Y-0097 Raven #1 well on file at BOEM). Core photos show interbedded plane-laminated sandstone, bioturbated sandstone and siltstone(?), and relatively coarse-grained sandstones (fig. 10b). The coarser-appearing sand in the photos is heavily oil-stained. Descriptions of sidewall cores taken between 1,760 and 3,705 feet indicate interbedded conglomerate, pebbly sandstone, sandstone, siltstone, and claystone (some tuffaceous)—conglomeratic lithologies were noted only above a depth of 2,730 feet. Many of the coarser lithologies represented in the sidewall cores were described as having "good" to "excellent" oil shows as indicated by visible staining, odor, and oil fluorescence characteristics.

The presence of residual hydrocarbon in the Saddle Mountain section raises a number of important questions. Hydrocarbon appears to be present only in friable sandstone. Sandstone beds above and below the hydrocarbon occurrence, although highly weathered, are cemented with diagenetic clay minerals and calcite (fig. 6c). What controlled the distribution of hydrocarbons in this succession (and in the Raven #1 well)? What was the relative timing of clay mineral precipitation in pores and hydrocarbon migration? What was the relative timing of calcite replacement (and cementation?) relative to clay mineral precipitation and hydrocarbon migration? Generally, clay cementation is early, probably prior to hydrocarbon generation and migration. Although this conclusion is subjective, it appears that calcite is locally replacing the authigenic clay (that is, clay preceded calcite cementation). Answers to these questions are important for understanding the oil potential in lower Cook Inlet.

The presence of hydrocarbon shows at widely scattered locations in lower Cook Inlet, including the Saddle Mountain succession (this report), a reported hydrocarbon seep along the shoreline south of Kamishak Bay west of Cape Douglas (Magoon, unpublished field notes), numerous oil seeps on the Iniskin Peninsula (Detterman and Hartsock, 1966; Blasko, 1976), and numerous oil shows in the Raven #1 well all indicate the presence of mature source rock at depth underlying a relatively large area in lower Cook Inlet. Geochemical evidence presented above suggests oil in the Saddle Mountain section and Raven #1 well was derived from marine mudstones in the Middle Jurassic Tuxedni Group.

ACKNOWLEDGMENTS

Les Magoon (USGS emeritus) and Bob Swenson (Alaska State Geologist) reviewed the manuscript and offered many constructive suggestions for its improvement. Kirk Sherwood (Bureau of Ocean Energy Management [BOEM]) provided information on drill stem tests conducted by ARCO in the Raven #1 well in the Federal OCS waters of lower Cook Inlet. Shaun Peterson (Alaska Division of Oil & Gas) kindly provided LePain with the Raven #1 well files that he obtained from BOEM. Funding for our work in lower Cook Inlet was provided by the State of Alaska and Apache Corporation.

REFERENCES CITED

Blasko, D.P., 1976, Oil and gas seeps in Alaska: Alaska Peninsula, Western Gulf of Alaska: U.S. Bureau of Mines, 78 p.

Bureau of Ocean Energy Management, Well data for OCS Y-0097 Raven 1 well, lower Cook Inlet, Alaska

Detterman, R.L., and Hartsock, J.K., 1966, Geology of the Iniskin–Tuxedni region, Alaska: U.S. Geological Survey Professional Paper 512, 78 p., 7 plates, 15 tables.

Detterman, R.L., and Miller, J.W., 1985, Kaguyak Formation—An Upper Cretaceous flysch deposit, *in* Bartsch-Winkler, S., and Reed, K.M., editors, The United States Geological Survey in Alaska: Accomplishments during 1983: U.S. Geological Survey Circular 945, p. 49–51.

Finzel, E.S., 2010, Geodynamics of flat-slab subduction, sedimentary basin development, and hydrocarbon systems along the southern Alaska convergent plate margin: West Lafayette, Indiana, Purdue University, unpublished Ph.D. dissertation, 411 p.

Hastings, D.S., Robinson, A.G., and Robinson, N.M., Jr., 1983, Stratigraphy, depositional history, and reservoir potential of Cretaceous and early Tertiary rocks of lower Cook Inlet, Alaska [abs.]: American Association of Petroleum Geologists Bulletin, v. 67, no. 3, p. 480.

Keller, S.A., and Reiser, H.N., 1959, Geology of the Mount Katmai area, Alaska: U.S. Geological Survey Bulletin 1058-G, 298 p.

Magoon, L.B., and Anders, D.E., 1992, Oil-to-source-rock correlation using carbon-isotopic data and biological marker compounds, Cook Inlet–Alaska Peninsula, Alaska, *in* Moldowan, J.M., Albrecht, P., and Philp, R.P., eds., Biological Markers in Sediments and Petroleum: New Jersey, Prentice Hall, p. 241–274.

Magoon, L.B., and Egbert, R.M., 1986, Framework geology and sandstone composition, *in* Magoon, L.B., ed., Geologic studies of the lower Cook Inlet COST No. 1 well, Alaska outer continental shelf: U.S. Geological Survey Bulletin 1596, p. 65–90.

Magoon, L.B., Griesbach, F.B., and Egbert, R.M., 1980, Nonmarine Upper Cretaceous rocks, Cook Inlet, Alaska: American Association of Petroleum Geologists Bulletin, v. 64, no. 8 p. 1,259–1,266.

North American Commission on Stratigraphic Nomenclature, 1983, North American Stratigraphic Code: American Association of Petroleum Geologists Bulletin, v. 67, p. 841–875.

Swenson, R.F., 2003, Introduction to Tertiary tectonics and sedimentation in the Cook Inlet basin, *in* Dallegge, T.A., compiler, 2001 Guide to the petroleum geology and shallow gas potential of the Kenai Peninsula, Alaska: Alaska Division of Geological & Geophysical Surveys Miscellaneous Publication 128, p. 10–19.

Wilson, F.H., Hults, C.P., Schmoll, H.R., Haeussler, P.J., Schmidt, J.M., Yehle, L.A., and Labay, K.A., 2009, Preliminary geologic map of the Cook Inlet region, Alaska—Including parts of the Talkeetna, Talkeetna Mountains, Tyonek, Anchorage, Lake Clark, Kenai, Seward, Iliamna, Seldovia, Mount Katmai, and Afognak 1:250,000-scale quadrangles: U.S. Geological Survey Open-File Report 2009-1108, 54 p., 1 table, 2 map sheets, scale 1:250,000.